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# *Bacillus subtilis* impacts nutrient availability to enhance agricultural and environmental sustainability

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## ABSTRACT

Fertilizer wastage is the major reason for decreasing productivity, soil health, and increasing environmental pollution. Proper nutrient management practices like controlled-release fertilizers and precise timing and placement, are essential for sustainable agriculture. Bioactive *Bacillus subtilis* coated fertilizers (BSF) play an important role in plant nutrient availability and less nutrient loss due to controlled nutrient release. This study aimed to explore the potential of *Bacillus subtilis* in nutrient management for agricultural and environmental sustainability. *Bacillus subtilis* can produce protective endospores, and its role in bioremediation contributes to its effectiveness. It enhances plant growth, controls pathogens, and promotes sustainable practices. It aids in bioremediation by degrading organic pollutants. Future research aims to optimize these formulations for specific crops and environmental conditions. BSF can further reduce the environmental impact ensure sustainable nutrient delivery and understand beneficial impacts on soil health and sustainable agriculture.

## KEYWORDS

Bioactive fertilizer; *Bacillus subtilis*; Soil and plant health; Sustainable agriculture

## ARTICLE HISTORY

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## Introduction

Fertilizer wastage in agriculture and environmental management is a major issue [1,2]. Runoff, leaching, and volatilization are processes that lead to water pollution, groundwater contamination, and reduced yield efficiency. Proper nutrient management practices such as timing and placement of fertilizers and slow-release fertilizers are valuable for sustainable agriculture [3]. Bioactive fertilizers (BF) are essential in agriculture for improving nutrient use efficiency, reducing nutrient losses, and promoting sustainable practices [4]. BF offers controlled nutrient release, protection against environmental factors, and enhanced nutrient uptake by plants. BF also reduces environmental impact by minimizing water, air, and greenhouse gas emissions associated with fertilizer use. BF also enhance crop yields and quality by providing nutrients more efficiently [5,6].

*Bacillus subtilis* (BS) is a Gram-positive bacterium, that has numerous applications in agriculture, industry, and bioremediation [7,8]. BS resilience, ability to produce protective endospores, and role in bioremediation contribute to its effectiveness [9]. BS is a versatile bacterium found in soil, used in agriculture, industry, and bioremediation. Its durable endospore, secreted enzymes, and antimicrobial compounds enhance plant growth, control pathogens, and promote sustainable practices [10]. BS also aids in bioremediation by degrading organic pollutants, highlighting its importance in environmental cleanup [11].

Replacing 50% of urea with biofertilizer containing BS reduces nitrogen loss by 54% in farmland, increases nitrogen use efficiency by 11.2%, and increases yield by 5.0%. It slows nitrification by decreasing bacterial amoA, enhances denitrification by increasing denitrifying genes, reduces nitrogen-fixing gene nifH abundance, and increases Bacteroidetes and Chloroflexi, making it an effective non-point pollution control strategy [12].

*Bacillus subtilis* is a biocontrol agent that protects plants from pathogenic microorganisms [13]. It produces antimicrobial compounds, such as lipopeptides and antibiotics, which inhibit the growth of various plant pathogens. These compounds have strong antifungal and antibacterial properties, disrupting fungi's cell membranes and inhibiting fungal growth. Bacitracin, an antibiotic, inhibits bacterial cell wall synthesis, killing susceptible bacteria [14,15]. *Bacillus subtilis* also competes for niche space, reducing pathogen growth resources. It induces plant defense mechanisms, producing defense-related compounds in plants. Biofilms on plant surfaces prevent pathogen colonization and facilitate nutrient uptake and water retention. This makes it an environmentally friendly alternative to chemical pesticides, contributing to the ecological balance in agricultural systems [16,17]. This study aims to explore the importance of *Bacillus subtilis* in improving nutrient management, enhancing plant growth, controlling pathogens, promoting sustainable practices, and improving soil health in agriculture.

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## Role of *Bacillus subtilis* in agricultural and environmental sustainability

*Bacillus subtilis* induces systemic resistance (ISR) in plants, enhancing their defense mechanisms against pathogens [18]. ISR involves activating defense-related genes, producing antimicrobial compounds, and priming plant defenses. These genes encode proteins that inhibit pathogen growth, and the bacteria produce lipopeptides that directly inhibit pathogen growth [19]. ISR priming allows plants to respond more rapidly to subsequent pathogen attacks, providing enhanced protection against diseases. Indirect defense mechanisms, such as signaling molecules, can also enhance resistance [20]. ISR provides long-lasting protection, reducing the need for chemical interventions. *Bacillus subtilis* can coexist with beneficial microorganisms, enhancing plant health and protection [21].

*Bacillus subtilis* enhances plant tolerance to abiotic stresses like drought, salinity, and heavy metals through various mechanisms like induced systemic tolerance, production of antioxidants and enhanced nutrient uptake [22,23]. It helps maintain cellular water balance by producing osmoprotectants like proline and trehalose during drought, improves water use efficiency by promoting a well-branched root system, regulates stomatal closure, maintains ion homeostasis by reducing toxic ions and enhancing essential nutrients, detoxifies heavy metals, enhances the antioxidant defense system by producing enzymes like superoxide dismutase, catalase, and peroxidase, and induces stress-responsive genes [24,25]. These mechanisms help plants thrive in challenging environments and contribute to sustainable agriculture in adverse growing conditions [26].

*Bacillus subtilis* is a crucial microorganism that enhances soil health by promoting beneficial microorganisms (by producing antimicrobial compounds and enzymes that can suppress harmful pathogens and promote the growth of beneficial microorganisms in the soil), enhancing soil structure (by producing exopolysaccharides and other compounds that can improve soil structure, helps in binding soil particles together, creating aggregates that improve soil porosity, water infiltration, and aeration), and enhancing nutrient cycling [27,28]. This leads to improved soil fertility and productivity, making it a valuable part of sustainable agricultural practices. *Bacillus subtilis* promotes the growth of beneficial soil microorganisms, suppresses soilborne pathogens, and improves soil structure through the production of extracellular polymeric substances [29,30]. It also plays a role in nutrient cycling, solubilizing nutrients, and mineralizing organic matter. It also contributes to the decomposition of organic matter, stabilizing soil pH, and reducing soil erosion [31,32].

## Conclusions

*Bacillus subtilis* is promised to play a pivotal role in sustainable agriculture through innovative applications and research areas. One such development is bioactive coated fertilizers containing *Bacillus subtilis*, which can revolutionize nutrient management and crop health. These bioactive fertilizers can improve nutrient efficiency, reduce environmental impacts, and enhance plant growth and nutrient uptake. Future research aims to optimize these formulations for specific crops and environmental conditions. Biodegradable coatings for bioactive fertilizers containing *Bacillus subtilis* could reduce environmental impact and ensure sustainable nutrient delivery. Research is also underway to explore the synergistic effects of *Bacillus subtilis* in microbial consortia, precision agriculture, bioremediation, and climate resilience. These developments will drive innovation and sustainability in agriculture.

Fertilizer wastage in agriculture is a significant issue, causing water pollution and reduced yield efficiency. Proper nutrient management practices, including slow-release fertilizers and controlled timing, are crucial for sustainable agriculture. *Bacillus subtilis* coated BF improve nutrient use efficiency, reduce losses, and promote sustainable practices. Innovative applications of this bioactive coated fertilizers can revolutionize nutrient management and promote sustainable agriculture.

## Disclosure Statement

No potential conflict of interest was reported by the authors.

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